Digital state controller for a high-voltage generator using the mixed-mode modulation method

The invention relates to a power supply unit, in particular for supplying high-voltage power, to an X-ray device having a power supply unit and to a method of controlling a power supply unit.

Particularly in the high-voltage sector, power supply units are used for example as power supply for X-ray tubes, in which, by means of a converter circuit, an intermediate circuit DC voltage is converted into a switched voltage, for example into a pulse-width-modulated (PWM) or pulse-frequency-modulated (PFM) voltage. A resonant circuit that has a transformer is fed with the switched voltage. On the secondary winding an output voltage is tapped off – where appropriate after rectification and/or passing through a multiplier circuit to increase the voltage. The resulting output voltage can be used, for example, to supply an X-ray tube.

In high-voltage generators, the aim of development is to be able to construct small and compact generators. In order to be able to make the switching device smaller and more compact for this purpose, a reduction in the switching losses is required.

WO 01/37416 proposes an actuation method for a power supply unit, in which various operating modes are provided for low, medium and high output voltages. The operating modes differ in terms of the type of actuation of the switching device and thus in terms of the switched voltage supplied. In a first operating mode for low output powers, the switching device is actuated in a non-resonant manner (i.e. below half the resonant frequency of the circuit) at an essentially fixed frequency by varying the sampling conditions (pulse width modulation, PWM).

In a second operating mode for medium output powers, the output power is controlled by changing the switching frequency, but with the switching frequency still remaining below half the resonant frequency.

Finally, in a third operating mode for high output powers, the switching frequency is above half the resonant frequency. Fully resonant operation takes place at maximum output power. In this case, too, the output power is adjusted by changing the switching frequency (PFM).

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This type of actuation is referred to as mixed-mode modulation. It has been found that the switching losses can as a whole hereby be considerably reduced.

Particularly in X-ray applications, high demands are placed on the control of the output voltage. For instance, a rise time that is as short as possible and an overshoot at the end of the voltage run-up that is as small as possible are to be strived for in order to quickly reach the steady state and avoid exposing the patient to a dose of radiation that is undesirably high.

EP 1 081 839 describes a series resonant converter, in particular to be used for X-ray devices, having a control circuit. The control circuit is designed as a digital control circuit having control in the state space. Besides the output voltage, the voltage across the resonant capacitor is used as control variable. In order to rule out destruction of components on account of overloading, this control variable is subject to a limit function.

While the control strategy described in EP 1 081 839 gives good results in conventional switching devices, problems arise in the case of highly non-linear control paths. A power supply circuit operated with mixed-mode modulation is one example of such a non-linear control path.

It is an object of the invention to specify a power supply unit having a control device and also a method of controlling a power supply unit, where good control is achieved even in the case of highly non-linear behavior. Furthermore, it is an object of the invention to specify an X-ray device having a power supply unit controlled in this way.

This object is achieved by a power supply unit as claimed in claim 1, an X-ray device as claimed in claim 10 and a method as claimed in claim 11. Dependent claims relate to advantageous embodiments of the invention.

The power supply unit comprises a switching device, for example a half or full bridge. As a result, a resonant circuit, preferably having a resonant capacitor and a transformer, is supplied with power. The switching device can be controlled. Actuation is predefined by a control device.

The control device according to the invention is preferably designed as a digital control device. At least one correcting variable is calculated. Preferably, a scalar correcting variable is calculated, from which the actuation for the switching device. i.e. switching frequency and pulse width or pulse duty factor of the switched voltage that is to be generated, can be determined unambiguously.

The control device according to the invention processes, as first actual value, a value which depends on the output voltage. In addition, a second actual value can be

processed, which depends on the current flowing through the resonant circuit elements. Preferably, this is the voltage across a resonant capacitor. The actual values are linked according to the respectively selected control structure for calculating the correcting variable. Controller coefficients are used, by which processed variables are multiplied.

5   The particular feature of the solution according to the invention is that one or more, preferably all, controller coefficients used can change not in a constant manner but rather as a function of the operating point. Within the digital control device, they can be formed, for example, as a look-up table, so that they assume different values in different operating states of the power supply unit.

10   The respective operating point can be given by the electrical variable of the power supply unit or by a variable of the control, or by a combination of a number of variables. Preferably, those variables will be used that are a measure of the power supplied.

          In order that a variation of the controller coefficients, which for example may be subjected to extremely large variations when changing between different operating modes

15   in the case of mixed-mode modulation, does not lead to a discontinuous change in the correcting variable, according to the invention a controller that operates differentially is proposed. That is to say that the controller does not process measured values of the actual values themselves, but rather changes of such measured values over time. In the case of the proposed digital control device, therefore, the differences between sample values at various

20   sampling instances, preferably at sampling instances that directly follow one another, are calculated and used in the calculation of the correcting variable. The differential principle makes it possible for there to be a continuous starting variable despite high variation in the controller parameters.

          It has been shown that, using such a controller, the high demands placed on a

25   controlled high-voltage power supply can be met, even for X-ray tubes, despite the use of mixed-mode modulation.

          In the control, the intermediate circuit voltage can be assumed to be constant. Since, however, this may also fluctuate for example as a function of the load, in order to achieve even better control properties it is proposed, according to a development of the

30   invention, that the control device processes the intermediate circuit voltage as an additional input variable. Within the control device, any deviations of the intermediate circuit voltage can then be compensated.

          As already mentioned, preferably some or all of the controller coefficients are dependent on the operating point. They may be stored in corresponding tables. The

coefficients can be calculated by a complete controller design being carried out for each operating point. The respective tables for the operating-point-dependent controller coefficients can be one-dimensional or multidimensional, that is to say that the respective controller coefficient is dependent on one or more variables. Two-dimensional look-up tables are preferred, in which the respective controller coefficient is determined as a function of a pair of values from two indexing variables. It is preferred that the first indexing variable depends on the correcting variable calculated by the controller and the second indexing variable depends on one or more of the processed actual values. In a preferred embodiment, a time-delayed correcting variable is used as first indexing variable and a difference between two processed actual values, namely the output voltage and the voltage across the resonant capacitor, is used as second indexing variable.

The preferred basic structure of the control device is that of a differential PI controller. In a preferred embodiment, the control deviation and difference values of the processed actual values and a coupled-back, time-delayed difference value of the correcting variable are in each case multiplied by controller coefficients and summed. The result is in turn temporally summed in order to calculate the correcting variable. Preferably all controller coefficients can change as a function of the operating point.

According to a development of the invention, a specific control is provided by means of which the destruction of components on account of overloading is prevented. In a series resonant converter, this relates in particular to the resonant current, that is to say the current through the series resonant elements. By limiting this current or the voltage across the resonant capacitor, overloading can be prevented. For the purpose of such limiting, the control device comprises, in addition to the first controller unit for controlling the output voltage, a second controller unit which predefines a second correcting variable in order to regulate the voltage across the resonant capacitor to a maximum value. If the correcting variable predefined by the first controller unit exceeds the correcting variable predefined by the second controller unit, then the correcting variable is limited to the latter value.

In this way, dynamic limiting is achieved which during normal operation does not interfere with the actual control. Limiting only takes place if the first controller unit predefines a correcting variable that could lead to a critical operating state. On account of this limiting, overall a faster response time can be achieved since the first controller unit can be designed to operate the components of the power supply unit closer to their power limit.

According to a development of the invention, the control device is designed in a digital manner, for example by means of a DSP which executes a corresponding program.

If at high resonant frequencies the timing intervals are too short to carry out all necessary calculations, it may be provided that only measured values of some of the timing intervals are processed, for example the measured values during every second, third, etc. timing interval.

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The invention will be further described with reference to examples of embodiments shown in the drawing to which, however, the invention is not restricted.

Fig. 1 shows a schematic circuit diagram of a high-voltage power supply unit for an X-ray tube.

10   Fig. 2 shows a circuit diagram of a switching device.

Fig. 3 shows an equivalent circuit diagram of a resonant converter.

Figs. 4a-4c show a schematic diagram of the variation over time of a switched voltage and of a resonant current in a first, second and third operating mode.

Fig. 5 shows the variation over time of currents and voltages in Fig. 3.

15   Fig. 6 shows a diagram with the mutual dependency of the variables T_W, T_P and T_{PW}.

Fig. 7 shows a schematic diagram of a power supply unit with control.

Fig. 8 shows a controller diagram of a PI controller.

Fig. 9 shows a controller diagram of a differential PI controller.

20   Fig. 10 shows a controller diagram of a control device having two control units.

Fig. 11 shows a controller diagram having a differential PI controller with operating-point-dependent controller coefficients and compensation for the intermediate circuit voltage.

25   Fig. 12 shows a controller diagram of one embodiment of a complete control device.

Fig. 1 shows a power supply unit 10 for an X-ray tube 12. An AC voltage
30   supply 14 – for example a connection to the power supply network – supplies, after rectification by means of a rectifier unit 16, an intermediate circuit voltage U_Z, with which a switching unit 18 is supplied. The switching unit 18 converts the intermediate circuit DC voltage U_Z into a switched voltage with which a resonant circuit 20 having a series capacitor C and a transformer T is supplied. On the secondary of the transformer T, an output voltage

is generated via a multiplier circuit 22 that is known per se, with which output voltage the X-ray tube 12 is supplied.

Fig. 2 shows a circuit diagram of the switching device 18. In the example shown, this is a full bridge circuit, in which the input DC voltage U_Z is converted into a

5   switched output voltage U_{WR} by means of four controlled switches S1, S2, S3, S4. Antiparallel diodes D1, D2, D3, D4 are in each case assigned to the switches S1, S2, S3, S4. The current flowing between the half bridges is designated I.

As shown in Fig. 1, the resonant circuit that is supplied by the switching unit 18 comprises a series capacitor C and a transformer T. By making a few simplifications

10 (replacement of the multiplier circuit 22 by a bridge rectifier 24 and an ideal transformer having a constant winding ratio, infinitely high main inductance of the transformer T, neglecting of losses during rectification and neglecting of the parasitic capacitance of the transformer T) and also the transformation of all electrical variables to the primary of the transformer T, the equivalent circuit diagram shown in Fig. 3 is obtained. The voltage across

15 the resonant capacitor C is designated u_C. The leakage inductance of the transformer T is designated L and the voltage across this is designated u_L. The ohmic loss of the transformer T is represented by the resistor R. Across the ideal rectifier 24 there is the AC voltage u_{GR}, from which the voltage u_{out} is generated that supplies a load capacitor C_g and a load resistor R_L which represent the tube 12.

20 The power supply unit 10 is operated with mixed-mode modulation as described in WO 01/37416. The content of said document is fully incorporated herein in relation to this actuation method. In the mixed-mode modulation that is used, three different operating modes with different actuation are distinguished. These three operating modes will be described below with reference to Figs. 4a, 4b and 4c:

25 In a first operating mode, the switching device 18 is actuated such that the switched voltage U_{WR} that is supplied is a pulse-width-modulated voltage. A low, fixed switching frequency is used. Fig. 4a shows, for this first operating mode, the variation of the current I and the actuation of the switches S1, S2, S3, S4 on the basis of a switching variable S (when S=1, S1 and S4 are on and S2 and S3 are off; when S=0, all switches are off; when

30 S=-1, S2 and S3 are on and S1 and S4 are off). Control is effected by varying the degree of sampling. The first operating mode is used for low output power.

In the second operating mode, the degree of sampling is constantly at the maximum, i.e. half the resonant period. The switching frequency can vary between the low frequency used in the first operating mode and half the resonant frequency of the circuit 20.

Fig. 4b shows the variation of the current in the case of this actuation. The output power is adjusted by means of pulse frequency modulation (PFM). The second operating mode is used for medium output powers.

In the third operating mode, the circuit 20 is operated in a resonant manner. The switching frequency can vary above half the resonant frequency of the circuit 20. The pulse width is obtained from the zero crossing of the resonant current. The active pulse is terminated with the zero crossing. Fig. 4c shows the corresponding variation over time of the electrical variables. Using the excess resonance, the output power is adjusted by means of pulse frequency modulation. The third operating mode is used for operation at high output powers.

Fig. 5 shows the variation over time of the variables $u_C(t)$, u_{WR} and $i(t)$. Some variables will be defined on the basis of this diagram. A timing interval begins with a zero crossing of the current ("Detect Zero" result). After a time T_W, an active phase begins in which the positive (S1, S4) or the negative (S2, S3) diagonal of the full bridge 18 is activated. The active phase lasts for an interval T_P and is terminated by the zero crossing of the current. After this, all switches are switched off. At the next zero crossing, a new timing interval begins with the opposite active phase. The values T_W and T_P are predefined by the control device. For easier handling, T_W and T_P are standardized to half the resonant frequency (which is known) of the resonant circuit 20. The three operating modes can then be characterized as follows in terms of T_W and T_P:

Low Power: $T_W = T_{W, max}$; $0 < T_P < 1$

Medium Power: $1 < T_W < T_{W, max}$; $T_P = 1$

High Power: $0 < T_W < 1$; $T_P = 1$.

As a result, it is possible to define a scalar value T_{PW}, by means of which the values T_P and T_W are in each case defined. Fig. 6 shows the non-linear relationship between T_P, T_W and T_{PW}.

In a symbolic representation, Fig. 7 shows how the power supply unit 10 is controlled. The voltage U_C across the resonant capacitor and the output voltage U_{out} are measured, sampled and fed to a controller 30. The controller 30 predefines a value T_{PW} as correcting variable, and this is converted in a driver 32 first into the values T_W and T_P and then into the corresponding actuation for the switches S1, S2, S3, S4. In addition, the controller 30 also processes sampled measured values of the intermediate circuit voltage U_z, to compensate for any fluctuations in this intermediate circuit voltage.

The functional blocks controller 30 and actuation 32 in Fig. 7 can be implemented in whole or in part as software solutions. A DSP implementation is preferred. When carrying out the calculations, in the high power mode only short time periods of less that the resonant period are available. If the resonant frequency of the controlled system is

5   high and thus the resonant period is short and these temporal framework conditions are too small to carry out the necessary calculations, an implementation can be selected in which the measurements are only carried out at every second "Detect Zero" result. In the time available, the measured values are digitized and the calculations to determine the correcting variable T_{PW} are carried out.

10   The control structure implemented by DSP is a digital state space control. Fig. 12 shows, in a controller diagram, the overall structure of the controller 30. However, before more details are given in respect of the implementation shown in Fig. 12, parts thereof will first be described individually.

Fig. 8 firstly shows the PI basic structure of the controller used. Actual values

15   U_{out} and $U_L = U_C - U_{out}$ are processed. The starting voltage U_{out} is to be controlled to a desired value U_{soll}. The processed actual values U_{out}, U_L are multiplied by controller coefficients k_{out}, k_L. The control deviation $U_{soll} - U_{out}$ is multiplied by a controller coefficient k_I and temporally summed, which corresponds to discrete integration. The value of the correcting variable $T_{PW, reg}$, which is delayed by a time unit, is multiplied by the controller

20   coefficient k_E. The variables that are in each case multiplied by the controller coefficients k_{out}, k_L, k_I, k_E are summed with signs as shown in Fig. 8 and subjected to a limit function in order to form the correcting variable $T_{PW, reg}$.

However, the controller coefficients k_{out}, k_L, k_I, k_E in Fig. 8 are generally not constant. Rather, they depend on the respective operating point of the power supply unit 10.

25   The variable U_L, where appropriate resolved by compensation for fluctuations of the intermediate circuit voltage U_Z, as mentioned below, and the control variable $T_{PW, reg, old}$ of the previous calculation interval are used as indexing variables for the operating point.

When calculating $T_{PW, reg}$ of the control structure shown in Fig. 8, in each case a set of controller coefficients k_{out}, k_L, k_I, k_E that corresponds to the current operating point is

30   used in the current calculation. The respective values of each of these coefficients are stored in a two-dimensional look-up table, where the respective values for k_{out}, k_L, k_I and k_E are stored for a number of pairs of values of the indexing variables U_L and $T_{pw, old}$. For a given, current operating point, i.e. actual values for U_L and $T_{PW, old}$, firstly the next pair of these indexing variables is determined from this look-up table and then the associated, stored value

for the respective controller coefficient is used. As an alternative to selecting the next pair, it would also be possible to interpolate the respective value of the controller coefficient in a suitable manner if there is sufficient calculation time to do so.

In order to fill the look-up table with the corresponding settings for the coefficients k_{out}, k_L, k_I, k_E for pairs of indexing values U_L, $T_{PW, old}$, a complete design of the controller is required for each operating point.

The following model can be used to determine the controller parameters. U_{out} and U_C are sampled states which are derived from the respective measured variables at the current zero crossing of the resonant current. The dynamic response of these variables is described by the state model

$$\begin{pmatrix} U_L \\ U_{out} \end{pmatrix}_{k+1} = \mathbf{A} \begin{pmatrix} U_L \\ U_{out} \end{pmatrix}_k + \mathbf{b}\, E(U_{L,k}, T_{PW,k})$$

where the state variable U_L is a composed variable

$$U_{L,k} = U_{C,k} - U_{out,k}.$$

$\mathbf{A}$ and $\mathbf{b}$ represent system matrices which depend on parameters of the power supply unit 10. The non-linear function E depends on the state variable U_L and the control variable T_{PW}. It is clearly defined by the converter parameters and the control method.

In order to design the controller, the non-linear function is linearized in an operating point (U_{L0}, T_{PW0}). The resulting linear model is expanded by two additional states. The state Σ represents the sum over the control deviation and is used to model the integral fraction, whereas the state T_{PWsys} serves to model a digital delay between calculation and switching on of a new manipulated value T_{PW}. This leads to an expanded system model

$$\begin{pmatrix} U_L \\ U_{out} \\ \Sigma \\ T_{PWsys} \end{pmatrix}_{k+1} = \begin{pmatrix} A & & 0 & b \\ & & 0 & \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} U_L \\ U_{out} \\ \Sigma \\ T_{PWsys} \end{pmatrix}_k + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} T_{PW} + \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} U_{soll}.$$

The parameters of a state controller

$$T_{PW} = -\begin{pmatrix} k_L & k_{out} & k_I & k_e \end{pmatrix} \begin{pmatrix} U_L \\ U_{out} \\ \Sigma \\ T_{PWsys} \end{pmatrix}$$

can be determined according to the pole placing method – i.e. a design by eigenvalue settings or pole settings (see, for example, O. Föllinger, "Lineare Abtastsysteme

[Linear sampling systems]", R. Oldenburg Verlag, 1982, Section 7.6). It is assumed that, in previous steps, firstly the desired dynamic properties of the system, such as rise time, maximum overshoot, etc., are predefined, and from these settings corresponding eigenvalues of the system matrix are determined. If an overshoot of the system is to be avoided

5   altogether, which is often the case, this requires purely real eigenvalues without any imaginary part.

The above-described design is carried out for all possible combinations of values $U_{L0,1}$ to $U_{L0,n}$ and $T_{PW0,1}$ to $T_{PW0,m}$. The controller parameters that are obtained are written into the various tables which are evaluated by the DSP as a function of the operating

10   point.

However, the fundamental PI controller structure as shown in Fig. 8 is not used directly in the controller 30. Rather, as shown in Fig. 9, this structure is expanded by a differential component. In this case, it is not the values per se of the actual values U_{out} and U_L and of the fed-back correcting variable $T_{PW, reg}$ that are used, but rather difference values of

15   the current sampling value to the previous sampling value. In Fig. 9, corresponding difference units Δ are additionally added to the basic structure (Fig. 8). By moving the temporal summation Σ behind the summation point, the correcting variable $T_{PW, reg}$ is again calculated from this. The advantage of the differential structure shown in Fig. 9 over the basic structure shown in Fig. 8 is that the operating-point-dependent changes of the controller

20   parameters have an effect firstly in the differential domain. By means of the subsequent temporal summation (discrete integration), a continuous change in the correcting variable $T_{PW, reg}$ is thus ensured even in the event of changes to the parameters k_{out}, k_L, k_I, k_E.

Fig. 10 shows two controller units 34, 36. The controller unit 34 shown on the left in Fig. 10 corresponds to the representation in Fig. 9 and is used to regulate the output

25   voltage U_{out} to the desired value U_{soll}.

The controller unit 36 shown on the right in Fig. 10 has the same structure as the controller unit 34. However, in the example shown, the controller parameters $k_{L, I}$, $k_{out, I}$, $k_{I, I}$, and $k_{E, I}$ are in this case not dependent on the operating point (in an alternative embodiment these parameters can also be dependent on the operating point). The control

30   deviation is formed from the actual value of the voltage across the resonant capacitor u_C and a fixedly set permissible maximum value $U_{C, max}$ for this voltage. The value $U_{C, max}$ corresponds to a value for the voltage across this capacitor at which there is no damage resulting from overloading of the circuit 20. The controller unit 36 supplies a correcting

variable ΔT_{PW} (still in the differential domain), by means of which actuation takes place such that the voltage U_C is regulated to the permissible maximum value $U_{C, max}$.

The two controller units 34, 36 are linked via a limit function. The correcting variable ΔT_{PW} supplied by the left-hand controller unit 34 is used (following temporal summation) for actuation for as long as it does not exceed the value predefined by the right-hand controller unit 36. The controller unit 36 is not used during normal operation. Only when values ΔT_{PW} that are too high are defined does the controller unit 36 limit ΔT_{PW} to the respectively dynamically determined maximum value at which a permissible U_C is still achieved.

Fig. 11 shows an additional extension of the controller structure of Fig. 9. In this case, a measured value for the intermediate circuit voltage U_Z is processed using an additional controller coefficient k_Z. In the functional blocks $\dfrac{U_{nenn}}{U_z}$, in each case multiplication takes place by a standardization factor which is equal to one if U_Z corresponds to the nominal value of U_{nenn}.

The controller coefficients k_{out}, k_L, k_l, k_E, k_Z are dependent on the operating point. In Fig. 11, arrows show how the look-up tables are oriented by the indexing variables $T_{PW, reg, old}$ and U_L (standardized to $\dfrac{U_{nenn}}{U_z}$).

The components explained above in connection with Figs. 8-11 are added to the completed controller 30 shown in Fig. 12. Shown on the left in Fig. 12 is a controller 40 for the output voltage (cf. Fig. 11). On the right, there is a controller 50 for limiting the correcting variable T_{PW} to a value which leads to a permissible voltage value U_C (cf. Fig. 10 and the associated explanations).

Finally, by means of the unit 32, using the relation shown in Fig. 6, the variables T_W and T_P are derived from the value T_{PW}.

By means of simulation and subsequent practical checking, it was possible to show that, using the shown controller structure, highly precise control can be achieved in the case of mixed-mode modulation.